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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant(s):	Darius Martin Sullivan and Nicholas Patrick Roland Hill		
Title:	CONTACT SENSITIVE DEVICE		
Application No.:	10/729,540	Filed:	December 5, 2003
Examiner:	Not yet assigned	Group Art Unit:	2857
Atty. Docket No.:	081-0003	Confirmation No.:	1918

May 14, 2004

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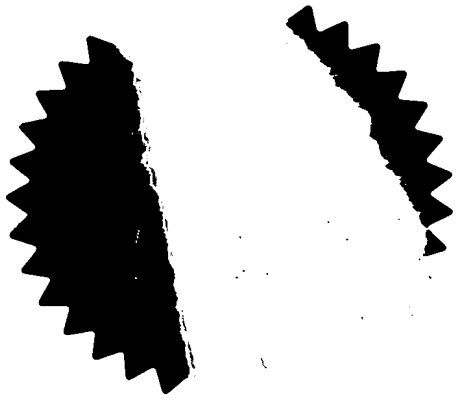

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0228512.0

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

New Transducers Limited
37 Ixworth Place
LONDON SW3 3QH
G.B.

Patents ADP number *(if you know it)* 07283476003

If the applicant is a corporate body, give the country/state of its incorporation

G.B.

4. Title of the invention

Contact Sensitive Device

5. Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

MAGUIRE BOSS
5 Crown Street
St. Ives
Cambridgeshire
PE27 5EB, GB

Patents ADP number *(if you know it)*

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DUPLICATE

TITLE: CONTACT SENSITIVE DEVICE

DESCRIPTION

TECHNICAL FIELD

The invention relates to contact sensitive devices.

BACKGROUND ART

Visual displays often include some form of touch sensitive screen. This is becoming more common with the emergence of the next generation of portable multimedia devices such as palm top computers. The most established technology using waves to detect contact is Surface Acoustic Wave (SAW), which generates high frequency waves on the surface of a glass screen, and their attenuation by the contact of a finger is used to detect the touch location. This technique is "time-of-flight", where the time for the

disturbance to reach one or more sensors is used to detect the location. Such an approach is possible when the medium behaves in a non-dispersive manner i.e. the velocity of the waves does not vary significantly over the frequency range of interest.

In WO01/48684 and PCT/GB2002/003073 to the present applicant, two contact sensitive devices and methods of using the same are proposed. In both applications, the device comprises a member capable of supporting bending wave vibration and a sensor mounted on the member for measuring bending wave vibration in the member and for transmitting a signal to a processor whereby information relating to a contact made on a surface on the member is calculated from the change in bending wave vibration in the member created by the contact.

By bending wave vibration it is meant an excitation, for example by the contact, which imparts some out of plane displacement to the member. Many materials bend, some with pure bending with a perfect square root dispersion relation and some with a mixture of pure and shear bending. The dispersion relation describes the dependence of the in-plane velocity of the waves on the frequency of the waves.

Bending waves provide advantages, such as increased robustness and reduced sensitivity to surface scratches, etc. However, bending waves are dispersive i.e. the bending wave velocity, and hence the "time of flight", is dependent on frequency. In general, an impulse contains a broad range of

component frequencies and thus if the impulse travels a short distance, high frequency components will arrive first. In WO01/48684 and PCT/GB2002/003073 a correction to convert the measured bending wave signal to a propagation signal from a non-dispersive wave source may be applied so that techniques used in the fields of radar and sonar may be applied to detect the location of the contact.

DISCLOSURE OF INVENTION

According to one aspect of the invention, there is provided a contact sensitive device comprising a member capable of supporting bending waves, three sensors mounted on the member for measuring bending wave vibration in the member, whereby each sensor determines a measured bending wave signal and a processor which calculates a location of a contact on the member from the measured bending wave signals, characterised in that the processor calculates a phase angle for each measured bending wave signal, then calculates a phase differences between the phase angles of least two pairs of sensors from which the location of the contact is determined.

According to a second aspect of the invention, there is provided a method of determining information relating to a contact on a contact sensitive device comprising the steps of providing a member capable of supporting bending waves and three sensors mounted on the member for measuring bending wave vibration in the member, applying a contact to the member at a location, using each sensor to determine a measured bending

wave signal and calculating the location of a contact from the measured bending wave signal characterised by calculating a phase angle for each measured bending wave signal, calculating a phase difference between the phase angles of at least two pairs of sensors and determining the location of the contact from the at least two calculated phase differences.

The following features may be applied to both the device and the method with the processor being adapted to provide many of the calculations or processing steps of the method.

Reflected waves may be suppressed by placing an absorber in contact with the edges of the member. The mechanical impedance of the absorber and member may be selected so as to minimise reflections of bending waves from the edges of the member. In particular, the impedances may be selected as that bending wave energy is strongly absorbed in a frequency band around a chosen frequency ω_0. The impedance of the absorber may be selected to be both resistive and compliant. The impedances may be selected to satisfy the following equation:

$$Z_T = -i Z_B(\omega_0)$$

where Z_T is the termination impedance of the absorber and Z_B is the mechanical impedance of the edge of the member.

The absorber may be made from foamed plastics which may have open or closed cells and may be polyurethane or polyvinylchloride. For example the foam may be a soft PVC predominantly closed cell foam such as MIERS™ or a medium to

high density, open cell polyurethane foam. The absorber may extend substantially around the periphery of the member. The absorber may act as a mounting which supports the member in a frame or to another surface.

The member may comprise a raised pattern on its surface whereby a contact drawn across the surface provides a variable force to the member to generate bending waves in the member. The pattern may be periodic, or quasi-periodic with a statistically well-defined spatial distribution of undulations. The pattern may be random whereby a contact travelling over the surface of the member generates a random bending wave signal. The random relief pattern may be formed by using an anti-reflective coating such as those which are found on many known transparent panels placed in front of electronic displays.

Each measured bending wave signal may be processed by a band-pass filter with a pass-band centred at the chosen frequency ω_0 and having a bandwidth of $\Delta\omega$. The bandwidth $\Delta\omega$ of the filter is preferably chosen to address the Doppler effect whereby a bending wave arrives at a point with a different frequency from its original frequency. Accordingly, the bandwidth preferably obeys the relationship:

$$\Delta\omega >> 2k(\omega_0)v_{max}$$

where v_{max} is the maximum lateral velocity of the contact across the surface, e.g. if the contact is provided by a

stylus, v_{max} is the maximum velocity that a user is capable of moving the stylus.

The phase of each filtered signal may be measured by comparison with a reference signal. The reference signal may have a frequency ω_0. The measured phase is the average phase difference between the input and reference signals, optimally measured over the interval $2\pi/\Delta\omega$. Alternatively, the reference signal may be derived from a filtered signal from a second sensor in which case, the measured phase is the phase difference between two input signals.

The phase differences may be calculated at intervals of $2\pi/\Delta\omega$ which may be intervals of less than 10ms. The reference and input signals may be fed to a phase detector. Output from the phase detectors may be fed through low-pass filters having frequency cut-offs of approximately $\Delta\omega/2$, then through digitisers and finally through a processor to calculate the phase angle θ.

The instantaneous phases, $\theta_l(t)$ and $\theta_m(t)$, of two measured bending wave signals may satisfy the phase difference equation equation:

$$\Delta\theta_{ml} = \theta_l - \theta_m = k(\omega_0)\Delta x_{ml} + 2\pi n_{lm}$$

where $\Delta x_{m1} = x_1 - x_m$ (x_m and x_1 being the distance from the contact location to each sensor labelled m and 1 respectively), and $k(\omega)$ is the wavevector. This equation may

be satisfied if the path length difference between two sensors is less than the coherence length of the bandpass filter, which is defined as

$$x_c = \frac{2\pi\omega_0}{\Delta\omega\, k(\omega_0)}$$

The coherence condition is therefore $\Delta x_{lm} << x_c$. If the coherence condition is not satisfied, the above phase equation may not be satisfied.

Thus, values of n_{lm} and the phase angle difference are required to determine the location of the contact. The shape of the member may be selected to constrain the magnitude of Δx_{lm} to values less than half of one wavelength, ie. $|\Delta x_{lm}| < \pi/k(\omega_0)$. In this case, where all possible values of Δx_{lm} satisfy the condition $|\Delta x_{lm}| < \pi/k(\omega_0)$, there is only one value of n_{lm} which is the integer n_{lm} satisfying $|\Delta\theta_{ml} - 2\pi n_{lm}| < \pi$. Alternatively, n may be estimated or inferred in some way.

Each phase angle difference in combination with the range of possible values of the integer n_{lm} may be used to generate a series of path length differences thereby defining a series of discrete hyperbolic curves on the surface of the member, denoting possible locations of the contact. The location of the contact may be determined by plotting each hyperbola defined by each path length difference and selecting a point at which a large number of the hyperbolae intersect or nearly intersect. This point is likely to be the true location of

the contact.

Where n_{1m} is unknown, the minimum number of series of hyperbolae required to determine the contact location is three and the likelihood of determining the correct location of the contact is increased by increasing the number of hyperbolae to be plotted. Multiple sensors may be used whereby a phase angle difference may be calculated for each pair of sensors thus generating multiple hyperbolae. In this embodiment, the minimum number of sensors is three.

Alternatively, where n_{1m} is unknown, the measured bending wave signal from each sensor may be divided into two or more discrete frequency bands whereby a phase angle difference may be calculated for each frequency band and for each pair of sensors. Although multiple phase angle differences may be calculated from a single pair of sensors, the phase angle differences at different frequencies are derived from the same path length difference. Thus the minimum number of sensors is three. The dividing of the frequency bands may be achieved by processing the bending wave signals by at least two band-pass filters having different pass-band frequencies. For example, using two band-pass filters having frequencies $\omega_0+\omega_\delta$ and $\omega_0-\omega_\delta$, the phase angle differences $\Delta\theta_a$, $\Delta\theta_b$ from two sensors may be defined as

$$\Delta\theta_a = k(\omega_0 + \omega_\delta)\Delta x + 2\pi n_a$$

$$\Delta\theta_b = k(\omega_0 - \omega_\delta)\Delta x + 2\pi n_b$$

where Δx is a single path-length difference defined by the contact and the position of the sensors.

Therefore the values of n_a and n_b may be selected so that the measured phase angle differences infer similar values of the path-length difference. There may be only one combination of values (n_a, n_b) for which this is possible. In this case the true value of the path-length difference may be determined. The correct combination (n_a, n_b) may be determined as the combination of values that minimise the expression:

$$\left| \frac{\Delta\theta_a - 2\pi n_a}{k(\omega_0 + \omega_\delta)} - \frac{\Delta\theta_b - 2\pi n_b}{k(\omega_0 - \omega_\delta)} \right|$$

The path length difference may then be estimated as:

$$\Delta x = \frac{1}{2}\left(\frac{\Delta\theta_a - 2\pi n_a}{k(\omega_0 + \omega_\delta)} + \frac{\Delta\theta_b - 2\pi n_b}{k(\omega_0 - \omega_\delta)} \right)$$

Where this process is repeated with two pairs of sensors, two path length differences may be determined, which in turn may be used to determine the location of the contact.

Alternatively, where n_{Lm} is unknown, an initial determination of the location of the contact may be made using the methods taught in WO01/48684 and PCT/GB2002/003073 (as summarised in Figure 11). Thereafter it may be assumed that the contact moves more slowly than the bending waves and hence that the phase angle differences change by small increments over the timescale Δt. Accordingly, each value of n may be chosen to minimise the change in path length difference.

Measured phase angle differences may contain random

errors which may result in the selection of incorrect values of n. This error may be alleviated by evaluating the likelihood of successive sequences of n, for example by a state-space estimator such as the well known Kalman filter. The sequence having the maximum measure of likelihood is selected.

The state-space estimator provides an estimate of the internal state of a system of which noisy measurements are made. A necessary input to the state-space estimator is a statistical description of the evolution of the system state. An example of such a state is the set of coordinates that describes the position and velocity of an object in contact with the member. It is widely known that the Kalman filter and other state-space estimators may provide a measure of likelihood that a sequence of observed, noisy measurements are consistent with the model of the system state.

A state-space estimator may therefore be employed to take a sequence of a pair of path-length differences (say Δx_{12} and Δx_{34}) taken at different times (say t_1, t_2, t_3,...), to estimate the system-state, i.e. the position and velocity of the contact, at those times. Moreover, the overall likelihood of those values of path-length difference being consistent with the model of the system may be evaluated.

Where the sequence of path-length differences are obtained from a sequence of phase-angle differences and a set

of integers ($n = n(t_1), n(t_2), n(t_3),\ldots$), the measure of likelihood generated by the state-space estimator may be used to infer the likelihood that the correct values of n were chosen. It follows that a method for choosing the correct sequence of integers, n, is to find the sequence for which the state-space estimator gives the maximum measure of likelihood.

As mentioned above, the state space estimator uses some statistical description of the evolution of the system state. A suitable model for the motion of the contact may be a simple random walk. Alternatively, the model may employ a detailed statistical description of how the user moves the pen. One example is a statistical description of how the user moves a pen while writing text or individual characters.

The processor may further be adapted to include in the determination procedure any available information about where the contact can be expected. For example, if the member is an input device for a graphical user interface where the user is presented with a choice of 'buttons' to press, it may be useful to assume that any contact on the member occurs within the discrete areas corresponding to the buttons.

Alternatively, a map of the probability at which a contact is likely to occur and which is based on the expected behaviour of the user may be used. The device may comprise a software application with a graphical user interface (GUI) which interacts with the operating system by means of an application program interface (API) in which the API is

adapted to generate the probability map. The probability map may be based on the location, size, and frequency of use of objects presented by the graphical user interface. The probability map may also be based on information about the relative likelihood of the various GUI elements being activated.

The following characteristics may apply to all embodiments of the invention. The device may comprise means for recording measured bending wave signals from the or each sensor over time as the contact moves across the member. The information relating to the contact may be calculated in a central processor. The sensors may be mounted at or spaced from an edge of the member. The sensors may be in the form of sensing transducers which may convert bending wave vibration into an analogue input signal.

The member may be in the form of a plate or panel. The member may be transparent or alternatively non-transparent, for example having a printed pattern. The member may have uniform thickness. Alternatively, the member may have a more complex shape, for example a curved surface and/or variable thickness.

The device is a purely passive sensor with the bending wave vibration and hence the measured bending wave signals being generated by an initial impact or by frictional movement of the contact. The contact may be in the form of a touch from a finger or from a stylus which may be in the form of a hand-

held pen. The movement of a stylus on the member may generate a continuous signal which is affected by the location, pressure and speed of the stylus on the member. The stylus may have a flexible tip, e.g. of rubber, which generates bending waves in the member by applying a variable force thereto. The variable force may be provided by tip which alternatively adheres to or slips across a surface of the member. As the tip moves across of the member a tensile force may be created which at a certain threshold, causes any adhesion between the tip and the member to break, thus allowing the tip to slip across the surface. The bending waves may have frequency components in the ultrasonic region (>20 kHz).

The member may also be an acoustic radiator and an emitting transducer may be mounted to the member to excite bending wave vibration in the member to generate an acoustic output. The frequency band of the audio signal of the transducer preferably differs from and does not overlap the frequency band of the measurements from the sensors. The audio signal may thus be filtered, for example, the audio band may be limited to frequencies below 20kHz, and the vibration measurements may be limited to frequencies above 20kHz. A sensor may have dual functionality and act as the emitting transducer.

The or each emitting transducer or sensor may be a bender transducer which is bonded directly to the member, for example

a piezoelectric transducer. Alternatively, the or each emitting transducer or sensor may be an inertial transducer which is coupled to the member at a single point. The inertial transducer may be either electrodynamic or piezoelectric.

A contact sensitive device according to the invention may be included in a mobile phone, a laptop or a personal data assistant. For example, the keypad conventionally fitted to a mobile phone may be replaced by a continuous moulding which is touch sensitive according to the present invention. In a laptop, the touchpad which functions as a mouse controller may be replaced by a continuous moulding which is a contact sensitive device according to the invention. Alternatively, the contact sensitive device may be a display screen, e.g. a liquid crystal display screen comprising liquid crystals which may be used to excite or sense bending waves. The display screen may present information relating to the contact.

BRIEF DESCRIPTION OF DRAWINGS

The invention is diagrammatically illustrated, by way of example, in the accompanying drawings, in which:-

Figure 1 is a schematic plan view of a touch sensitive device according to one aspect of the invention;

Figure 2 is a schematic perspective view of the device of Figure 1;

Figure 3 is a schematic side view of a one-dimensional beam;

Figure 4a is a graph showing the amplitude of the

reflection coefficient against frequency (Hz), the amplitude is unitless since it is a ratio;

Figure 4b is a graph showing the phase (radians) of the reflection coefficient in radials against frequency (Hz);

Figures 5a and 5b are schematic perspective views of alternative touch sensitive devices;

Figure 6 is a flowchart of a method of finding the location of a contact according to the invention;

Figure 7a is a schematic block diagram of apparatus used for calculating phase angles;

Figure 7b is a schematic block diagram of apparatus used with that of Figure 7a;

Figures 8a to 8d are plan views of apparatus according to the invention showing the hyperbolae of path length differences;

Figure 9 is a schematic block diagram of alternative apparatus used for calculating phase angles;

Figure 10 is a flow chart showing an alternative method of calculating the location of the contact;

Figure 11 is a flow chart showing a method of calculating the location of the contact using the dispersion corrected correlation function;

Figure 11a is a graph of dispersion corrected correlation function against time, and

Figure 12a is a schematic block diagram of a contact sensitive device which also operates as a loudspeaker, and

Figure 12b is a method of separating audio signal and measured bending wave signal in the device of Figure 12a.

DETAILED DESCRIPTION

Figure 1 shows a contact sensitive device 10 comprising a transparent touch sensitive plate 12 mounted in front of a display device 14. The display device 14 may be in the form of a television, a computer screen or other visual display device. A stylus 18 in the form of a pen is used for writing text 20 or other matter on the touch sensitive plate 12.

The transparent touch sensitive plate 12 is a member, e.g. an acoustic device, capable of supporting bending wave vibration. As shown in Figure 2, four sensors 16 for measuring bending wave vibration in the plate 12 are mounted on the underside thereof. The sensors 16 are in the form of piezoelectric vibration sensors and are mounted one at each corner of the plate 12. At least one of the sensors 16 may also act as an emitting transducer for exciting bending wave vibration in the plate. In this way, the device may act as a combined loudspeaker and contact sensitive device.

A mounting 22 made of foamed plastics is attached to the underside of and extends substantially around the periphery of the plate 12. The mounting 22 has adhesive surfaces whereby the member may be securely attached to any surface. The mechanical impedance of the mounting and plate are selected so as to minimise reflections of bending waves from the plate edges.

The relationship between mechanical impedance of the mounting and the plate may be approximated by considering the 1-d model shown in Figure 3. The model comprises a waveguide 34 in the form of a beam which terminates at an edge mounting 36 having a termination impedance. An incident wave 38 travelling down the waveguide 34 is reflected by the mounting 36 to form a reflected wave 40. The incident and reflected waves are plane waves travelling in the direction perpendicular to the edge. Assuming the mounting 36 satisfies the following boundary conditions:

(i) the termination impedance only couples into the lateral velocity, i.e. it does not provide any torque resistance; whereby the bending moment is equal to zero at the edge and

(ii) The ratio of the lateral shear force and the velocity at the edge is equal to the terminal impedance;

the reflection coefficient at the mounting is given by:

$$R(\omega)=\frac{-Z_T/Z_B(\omega)-i}{Z_T/Z_B(\omega)+1}$$

where Z_T is the termination impedance of the mounting and Z_B is the mechanical impedance of the end of the waveguide, given by

$$Z_B(\omega)=\frac{Bk(\omega)^3}{2\omega}(1+i)$$

where $k(\omega)$, is the wavevector which may be expressed in terms of the bending stiffness, B, and mass per unit area, μ, of the panel,

$$k = \left(\frac{\mu}{B}\right)^{1/4} \sqrt{\omega}$$

Thus, the reflection coefficient is determined by the ratio of the impedances at the end of the waveguide and the mounting. Furthermore, the impedance of the waveguide is proportional to the square root of frequency and is both real and reactive in equal weights (i.e. $\pi/4$ phase angle). Accordingly, the reflection coefficient is likely to be strongly frequency dependent.

The reflection coefficient vanishes, i.e. bending wave energy is strongly absorbed in a frequency band around ω_0, if the following condition is satisfied:

$$Z_T = -i Z_B(\omega_0)$$

Thus, the termination impedance of the mounting must have both real and imaginary components, or, equivalently, the mounting should be both resistive and compliant.

The plate may be, for example, 1 mm thick polycarbonate sheet which has mass per unit area, μ=1.196 kg m^{-2} and bending stiffness, B=0.38 N m. The equations above can be used to calculate the impedances of the plate and absorber required to strongly absorb bending wave energy around the chosen angular frequency $\omega_0 = 2\pi(900\ \text{Hz})$.

The impedance, per unit width for a 1mm beam approximation of the plate is

$$Z_B(\omega_0) = (1+i)\ 33.8\ \text{N s m}^{-2}.$$

The properties of the absorber which provide the desired absorption are thus:

Resistance per unit width,

$$\mathrm{Re}(Z_T) = \mathrm{Im}[Z_B(\omega_0)] = 33.8\,\mathrm{N s m^{-2}}.$$

Stiffness per unit width,

$$-i\,\mathrm{Im}(Z_T)\omega_0 = \mathrm{Re}[Z_B(\omega_0)]\omega_0 = 1.91\times10^5\,\mathrm{N m^{-2}}.$$

The reflection coefficient is a unitless complex number. Figures 4a and 4b are graphs showing the amplitude and phase of the reflection coefficient $R(\omega)$ varying with frequency. The amplitude of the reflection coefficient is zero and its phase is reversed for ω_0 approximately equal to 900Hz.

In Figures 5a and 5b, the plate 12 has uniform surface roughness in the form of a raised surface pattern 28,29. The stylus 18 is drawn across the surface along a path 30 and as it crosses a raised part or line of the pattern it generates bending waves 32 in the member. Thus contact from the stylus 18 provides a source of bending wave vibration in the member. In Figure 5a, the surface pattern 28 is a periodic pattern of raised crossed lines and in Figure 5b, the surface pattern 29 is a random relief pattern.

In the embodiments of Figures 2, 5a and 5b, as the contact moves over the rough surface of the member, bending waves radiate isotropically in the member from the point of contact. The displacement of the member at a distance, x, from the point of contact is related to the displacement at the

point of contact by a transfer function, $H(\omega; x)$. At distances larger than the wavelength, $\lambda = 2\pi / k(\omega)$, the transfer function can be approximated as,

$$H(\omega; x) \sim \frac{A}{\sqrt{k(\omega)x}} e^{-ik(\omega)x},$$

where A is a constant and $k(\omega)$, is the wavevector defined previously. Although $H(\omega; x)$ strictly only applies to bending waves on an infinite plate, since the mounting is strongly absorb bending wave vibrations, the relationship is satisfied. The transfer function shows that where a source of bending waves emits a purely sinusoidal frequency with angular frequency, ω_0, the phase difference $\Delta\theta_{12}$ between displacements at two locations which are at distances, x_1 and x_2, from the point of contact for the source is:

$$\exp(i\Delta\theta_{12}) = \exp[ik(\omega_0)(x_2 - x_1)]$$

This implies the following relationship between the phase angle difference, the path length difference (x_2-x_1) and an integer n_{12}.

$$\Delta\theta_{12} = \theta_1 - \theta_2 = k(\omega_0)\Delta x_{12} + 2\pi n_{12}$$

Figure 6 shows the steps in the method for using this equation to determine the contact location:

a) Measure a bending wave signal with each sensor to give measured bending wave signals $W_i(t)$ and $W_j(t)$,

b) Calculate the phase angles $\theta_i(t)$ and $\theta_j(t)$ of the measured

bending wave signals $W_i(t)$ and $W_j(t)$,

c) Calculate the difference between the two phase angles $\theta_i(t)$ and $\theta_j(t)$

d) Calculate the location of the contact from

$$\Delta\theta_{ij} = k(\omega_0)\Delta x_{ij} + 2\pi n_{ij}$$

Figure 7a shows a schematic block diagram of a device for calculating the phase angle θ_j of a bending wave signal $W_j(t)$ measured by one of the sensors. The signal $W_j(t)$ is a random signal and is thus uncorrelated over long time scales. The signal is first amplified by an amplifier 42 and then processed by an analogue band-pass filter 44 with a pass-band centred at ω_0 and a bandwidth of $\Delta\omega$.

A moving source of bending waves may demonstrate the Doppler effect, whereby a bending wave which has frequency ω_0 and is emitted by a source moving at velocity v towards a point on a member arrives at that point with a different frequency defined by $\omega_0 - k(\omega_0)v$. The maximum angular frequency shift between bending waves at two different points on the member is therefore $2k(\omega_0)v_{max}$, where v_{max} is the maximum velocity of the moving source. If the angular frequency shift becomes larger than the width of the band pass filter, the phase difference equation above does not hold. Accordingly, the bandwidth $\Delta\omega$ of the filter 44 is set to be greater than this maximum frequency shift and thus obeys the relationship:

$$\Delta\omega >> 2k(\omega_0)v_{max}$$

After processing by the filter 44, the resulting filtered signal $W'_j(t)$ is an amplitude and phase modulated carrier with frequency ω_0 and is defined by:

$$W'_j(t) = A_j(t)\sin[\omega_0 t + \theta_j(t)]$$

where $A_j(t)$ and $\theta_j(t)$ are the amplitude and phase of the signal. Both fluctuate over a timescale Δt determined by the bandwidth of the filter, namely $\Delta t = 2\pi/\Delta\omega$. The maximum frequency at which independent phase angle measurements may be taken from the output of the bandpass filter is Δt. Since a touch sensor typically provides an updated measurement of the contact position every 10ms, the condition for the minimum frequency of positional measurement is $\Delta t < 10ms$.

The filtered signal $W'_j(t)$ is then passed simultaneously to two analogue phase detectors 46. Such detectors are well known in the art, for example, see p644 of "The Art of Electronics" by Horowitz and Hill. Reference signals each having frequency ω_0 but a phase difference of $\pi/2$ are also fed to the two phase detectors. The outputs of the phase detectors are passed through low-pass filters 48 each having frequency cut-offs of approximately $\Delta\omega/2$. The outputs of the low-pass filters are proportional to $\cos(\theta)$ and $\sin(\theta)$ respectively. These outputs are then digitised by digitisers 50 and processed by processor 52 to give the phase angle θ.

Figure 7b shows how the reference signals used in Figure 7a may be generated. A second bending wave signal $W_i(t)$ is measured at a second senson. The signal is fed through an amplifier 42 and analogue band-pass filter to generate a filtered signal $W'_j(t)$. The filtered signal $W'_j(t)$ is fed direct to one phase detector 46 to form the reference signal. The signal is also fed to the second phase detector 46 via a device which shifts its phase by $\pi/2$. The phase shifted signal is used as the reference signal to the second phase detector 46.

Figures 8a to 8d shows how the phase angle differences and hence the path length differences may be used to calculate the location of the contact. The equation in step (d) of Figure 6 defines a hyperbolic curve which can be overlaid on the plate 12. Figure 8a shows the three hyperbolic curves 26 which are generated using three different values of n_{lm} and the calculated phase angle difference for a pair of sensors 16 mounted one on each end of the short sides of the plate 12. Similarly Figures 8b and 8c show the hyperbolic curves 26 which are generated by the phase angle difference and different values of n_{lm} for two other pairs of sensors. Figure 8d shows all the hyperbolic curves created by the sensors. The contact location 24 is the point of intersection of three hyperbolic curves, one from each pair of sensors. From the contact location 24, the correct value of n_{lm} may be

inferred.

A method of inferring n is implemented using the embodiment shown in Figure 9. The bending wave signal $W_1(t)$ measured by each sensor is simultaneously processed by two band-pass filters 48,54. Two phase angles, one for each filter, are calculated, for example as described in Figure 7. The filters 48, 54 have slightly different pass-band frequencies whereby two phase angle differences, one for each pass-band frequency, are provided by each pair of sensors.

The phase angle differences $\Delta\theta_a$, $\Delta\theta_b$ from the sensors may be defined as

$$\Delta\theta_a = k(\omega_0 + \omega_s)\Delta x + 2\pi n_a$$

$$\Delta\theta_b = k(\omega_0 - \omega_s)\Delta x + 2\pi n_b$$

where Δx is a single path-length difference defined by the contact and the position of the sensors.

The correct combination (n_a, n_b) may be determined as the combination of values that minimise the expression:

$$\left| \frac{\Delta\theta_a - 2\pi n_a}{k(\omega_0 + \omega_s)} - \frac{\Delta\theta_b - 2\pi n_b}{k(\omega_0 - \omega_s)} \right|$$

The path length difference may then be estimated as:

$$\Delta x = \frac{1}{2}\left(\frac{\Delta\theta_a - 2\pi n_a}{k(\omega_0 + \omega_s)} + \frac{\Delta\theta_b - 2\pi n_b}{k(\omega_0 - \omega_s)} \right)$$

Other pair of sensors may then be used to determine a series of path length differences and hence a series of hyperbolae. As in Figures 8a to 8d, the hyperbolae are plotted

and the point at which the largest number of hyperbolae intersect is likely to be the true location of the contact.

Figure 10 shows an alternative method for calculating the location of the contact from the equation above, namely

i. Measure a pair of bending wave signals $W_i(t)$ and $W_j(t)$, one signal being measured by a sensor;

ii. Calculate the dispersion corrected correlation function of the two signals using the method described in Figures 11 and 11a;

iii. Calculate the initial position of the contact using the dispersion corrected correlation function, as described in Figures 11 and 11a;

iv. Remeasure bending wave signals $W_i(t)$ and $W_j(t)$;

v. Calculate the phase angle of each signal - for example as described in Figures 7a and 7b;

vi. Calculate the difference between the phase angles;

vii. Select the value of n_{lm} which minimises the change in the path length difference;

viii. Plot the hyperbola defined by

$$\Delta\theta_{nl} = k(a_0)\Delta x_{nl} + 2\pi n_{lm}$$

ix. Repeat steps (iv) to (viii), remeasuring the bending wave signals at regular intervals Δt, for example $\Delta t = 2\pi/\Delta\omega$.

At step (viii), a minimum of two hyperbolae are required to determine the location of the contact since the location is determined from the intersection of the hyperbolae. Thus a

minimum number of two phase angle differences must be determined. Two phase angle differences may be generated by using two sensors and splitting the signal into two frequency bands as described in Figure 9. Alternatively, multiple sensors may be used so that multiple phase angle differences may be calculated using different pairs of sensors.

Figure 11 shows a method of calculating the dispersion corrected correlation function to reveal the difference in path length between the contact location and the sensors. The method set out below summarises the information in PCT/GB2002/003073. The method comprises the following steps:

(a) Measure two bending wave signals $W_1(t)$ and $W_2(t)$;

(b) Calculate the Fourier transform of $W_1(t)$ and $W_2(t)$ to arrive at $\hat{W}_1(\omega)$ and $\hat{W}_2(\omega)$ and hence the intermediate function $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$; where $\hat{W}_2^*(\omega)$ is the complex conjugate Fourier transform, t represents time ω is $2\pi f$ where f is frequency.

(c) Calculate a second intermediate function M(ω) which is a function of $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$

(d) and (e) at the same time as performing steps (a) to (c), the frequency stretching operation $f(\omega)=\nu(\mu/B)^{1/4}\sqrt{\omega}$ is calculated using the predetermined panel dispersion relation $k=(\mu/B)^{1/4}\sqrt{\omega}$.

(f) M(ω) and $f(\omega)=\nu(\mu/B)^{1/4}\sqrt{\omega}$ are combined to arrive at the dispersion corrected correlation function:

$G(t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}M[f(\omega)]\exp(i\omega t)d\omega$; and

(g) the dispersion corrected correlation function is plotted against time with a peak occurring at time t_{12} as shown in Figure 11a;

(h) Δx_{12} is calculated from t_{12}; Δx_{12} is the path-length difference between the path lengths x_1 and x_2 from the first and second sensors to the contact.

(i) Δx_{12} defines a hyperbolae which may be plotted as in Figure 7 to calculate the location of the contact.

As with the method of Figure 10, a minimum of two hyperbolae are required to determine the location of the contact. Thus the ways of generating more hyperbolae discussed above apply equally to this method.

The second intermediate function M(ω) may simply be $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$ which gives a standard dispersion corrected correlation function. Alternatively, M(ω) may be selected from the following functions which all yield phase equivalent functions to the standard dispersion corrected correlation function:

a) $M(\omega)=\frac{\hat{W}_1(\omega)\hat{W}_2^*(\omega)}{\left|\hat{W}_1(\omega)\hat{W}_2^*(\omega)\right|}$

b) $M(\omega)=\frac{\hat{W}_1(\omega)\hat{W}_2^*(\omega)}{\sqrt{\left|\hat{W}_1(\omega)\hat{W}_2^*(\omega)\right|}}$

c) $M(\omega)=\hat{W}_1(\omega)\hat{W}_2^*(\omega)\varphi\left|\hat{W}_1(\omega)\hat{W}_2^*(\omega)\right|$ where $\varphi(x)$ is a real valued

function

d) $M(\omega) = \hat{W}_1(\omega)\hat{W}_2^*(\omega)\psi(\omega)$ where $\psi(\omega)$ is a real valued function

Alternatively, M(ω) may be the function $\hat{D}(\omega)$ which is the Fourier transformation of the correlation function D(t):

$$D(t) = \int_{-\infty}^{\infty} W_1(t+t')W_2(t')dt'$$

The steps are calculate D(t); calculate $\hat{D}(\omega)$ and apply a frequency stretching operation to arrive at the dispersion corrected correlation function: $G(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\hat{D}[f(\omega)]\exp(i\omega t)d\omega$.

Alternatively, at step (f) the following dispersion corrected correlation function may be calculated:

$$G(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\hat{W}_1[f(\omega)]\hat{W}_2^*[f(\omega)]\,\phi_{12}[f(\omega)]\exp(i\omega t)d\omega$$

where

$$\phi_{12}^*(\omega) = \left|\sum_j \hat{W}_{1,j}(\omega)\hat{W}_{2,j}^*(\omega)\exp\left[-ik(\omega)\Delta x_j\right]\right|$$

where $\{\hat{W}_{1,j}(\omega)\}$ and $\{\hat{W}^*_{2,j}(\omega)\}$ are the Fourier transformation and complex conjugate Fourier transformation of two measured bending wave signals $\{W_{1,j}(t)\}$ and $\{W_{2,j}(t)\}$ and $\{\Delta x_j\}$ is the path-length difference.

A sensor may act as both the first and second sensor whereby, the dispersion corrected correlation function is an autocorrelation function. The autocorrelation function may be calculated applying the same steps for the dispersion

corrected correlation function using $W_1(t) = W_2(t)$.

Figure 12a shows a contact sensitive device which also operates as a loudspeaker. Figure 12b shows a method for partitioning the audio signal and measured signal into two distinct frequency bands so that the contribution of the audio signal to the processed measured signal is suppressed. The device comprises a member 106 in which bending waves are generated by an emitting transducer or actuator 108 and the contact. The emitting transducer applies an audio signal to the member 106 to generate an acoustic output. Before being applied to the member, the audio signal is filtered by a low pass filter 112 which, as shown in Figure 12b, removes the audio signal above a threshold frequency f_0.

As shown in Figure 12b, the contact generates a signal which has a power output which is substantially constant over a large frequency band. The signal from the contact and the audio signal sum to give a combined signal which is passed through a high pass filter 114 to remove the signal above the threshold frequency f_0. The filtered signal is then passed to a digitiser 116 and onto a processor 118.

CLAIMS

1. A contact sensitive device comprising a member capable of supporting bending waves, three sensors mounted on the member for measuring bending wave vibration in the member, whereby each sensor determines a measured bending wave signal and a processor which calculates a location of a contact on the member from the measured bending wave signals, characterised in that the processor calculates a phase angle for each measured bending wave signal and a phase difference between the phase angles of least two pairs of sensors so that at least two phase differences are calculated from which the location of the contact is determined.

2. A contact sensitive device according to claim 1 comprising an absorber at the edges of the member whereby reflected waves are suppressed.

3. A contact sensitive device according to claim 2, wherein the mechanical impedance of the absorber and the member are selected so as to minimise reflections of bending waves from the edges of the member.

4. A contact sensitive device according to claim 3, wherein the impedances are selected so that bending wave energy is strongly absorbed in a frequency band around a chosen frequency ω_0.

5. A contact sensitive device according to claim 4, wherein the impedances are selected to satisfy the following equation:

$$Z_T = -iZ_B(\omega_0)$$

where Z_T is the termination impedance of the absorber and Z_B is the mechanical impedance of the edge of the member.

6. A contact sensitive device according to claim 4 or claim 5, comprising a band-pass filter for filtering each measured bending wave signal, the filter having a pass-band centred at the chosen frequency ω_0 and a bandwidth of $\Delta\omega$.

7. A contact sensitive device according to claim 6, wherein the bandwidth $\Delta\omega$ of the filter obeys the relationship:

$$\Delta\omega \gg 2k(\omega_0)v_{max}$$

where v_{max} is the maximum lateral velocity of the contact.

8. A contact sensitive device according to any one of claims 2 to 7, wherein the absorber is made from foamed plastics.

9. A contact sensitive device according to any one of the preceding claims, wherein the member comprises a raised pattern on its surface whereby a contact drawn across the surface provides a force to the member to generate bending waves in the member.

10. A contact sensitive device according to claim 9, wherein the pattern is random whereby a contact travelling over the surface of the member generates a random bending wave signal.

11. A contact sensitive device according to claim 10, wherein the pattern is formed from an anti-reflective coating.

12. A contact sensitive device according to any one of the preceding claims, comprising at least two band-pass filters which have different pass-band frequencies and which simultaneously process the bending wave signals measured by a pair of sensors whereby a phase angle difference for each pass-band frequency is provided by a pair of sensors.

13. A contact sensitive device according to any one of the preceding claims, comprising four sensors on the member.

14. A contact sensitive device according to any one of the preceding claims, comprising means for determining the initial location of the contact using the dispersion corrected correlation function of pairs of measured bending wave signals and means for determining subsequent locations of the contact using the phase angle difference between pairs of measured bending wave signals.

15. A contact sensitive device according to any of the preceding claims, wherein the phase angle determining means comprises a phase detector.

16. A contact sensitive device according to claim 15, wherein the processor comprises a low-pass filter and a digitiser for determining the phase angles.

17. A contact sensitive device according to any one of the preceding claims, wherein the member is an acoustic radiator and an emitting transducer is mounted to the member to excite bending wave vibration in the member to generate an acoustic output.

18. A contact sensitive device according to claim 17, comprising means ensuring that the acoustic output and measured bending wave signals are in discrete frequency bands.

19. A contact sensitive device according to any one of the preceding claims, wherein the member is transparent.

20. A method of determining information relating to a contact on a contact sensitive device comprising the steps of providing a member capable of supporting bending waves and three sensors mounted on the member for measuring bending wave vibration in the member, applying a contact to the member at a location, using each sensor to determine a measured bending wave signal and calculating the location of a contact from the measured bending wave signal characterised by calculating a phase angle for each measured bending wave signal, calculating a phase difference between the phase angles of at least two pairs of sensors and determining the location of the contact from the at least two calculated phase differences.

21. A method according to claim 20, comprising suppressing reflected waves by placing an absorber at the edges of the member.

22. A method according to claim 21, comprising selecting the mechanical impedances of the absorber and the member so as to minimise reflections of bending waves from the edges of the member.

23. A method according to claim 22, comprising selecting the impedances so that bending wave energy is strongly absorbed in

a frequency band around a chosen frequency ω_o.

24. A method according to claim 23, comprising selecting the impedances to satisfy the following equation

$$Z_T = -iZ_B(\omega_0)$$

where Z_T is the impedance of the absorber and Z_B is the impedance of the edge of the member.

25. A method according to claim 23 or claim 24, comprising filtering each measured bending wave signal by a band-pass filter having a pass-band centred at the chosen frequency ω_o and a bandwidth of Δ_ω.

26. A method according to any one of claims 20 to 25, comprising applying the phase difference equation:

$$\Delta\theta_{ml} = \theta_l - \theta_m = k(\omega_0)\Delta x_{ml} + 2\pi n_{lm}$$

to determine the location of the contact, where θ_i is the phase angle of a measured bending wave signal, x_i is the distance from the contact location to each sensor, $\Delta x_{lm}=x_l-x_m$ is the path length difference of two sensors, $k(\omega)$ is the wavevector and n_{lm} is an unknown integer.

27. A method according to claim 26, comprising selecting the member to constrain the magnitude of Δx_{lm} to values less than one half of a wavelength so that n_{lm} is determined from $|\Delta\theta_{ml} - 2\pi n_{lm}| < \pi$.

28. A method according to claim 26, comprising determining an initial location of the contact using the dispersion corrected

correlation function of a pair of measured bending wave signals and selecting a value of n_{1m} which minimises change in the path length difference.

29. A method according to claim 26, comprising selecting a series of values of n_{1m}, combining the series of values with each phase angle difference to define a series of path length differences, plotting the series of graphs of the path length differences, and inferring the true value of n_{1m} from a point at which a large number of the graphs intersect.

30. A method according to any one of claims 20 to 29, comprising calculating multiple phase angle differences from the pairs of phase angles, plotting a graph of each path length difference and selecting a point at which a large number of the hyperbolae intersect to be the location of the contact.

31. A method according to any one of claims 20 to 30, comprising dividing the measured bending wave signals from each sensor into at least two discrete frequency bands and calculating a phase angle difference for a pair of sensors for each frequency band.

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Fig 1

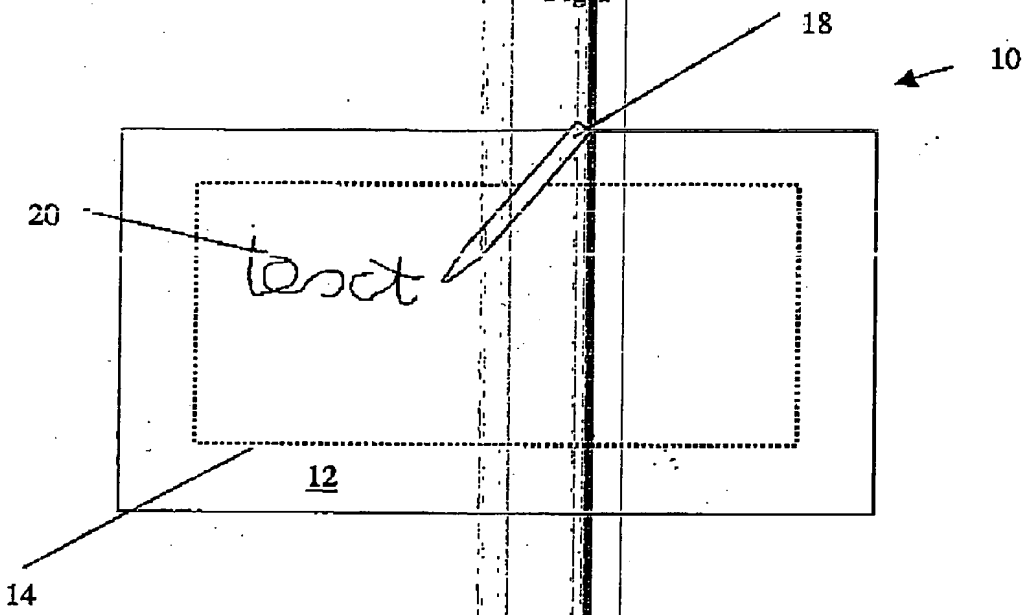

Fig 2

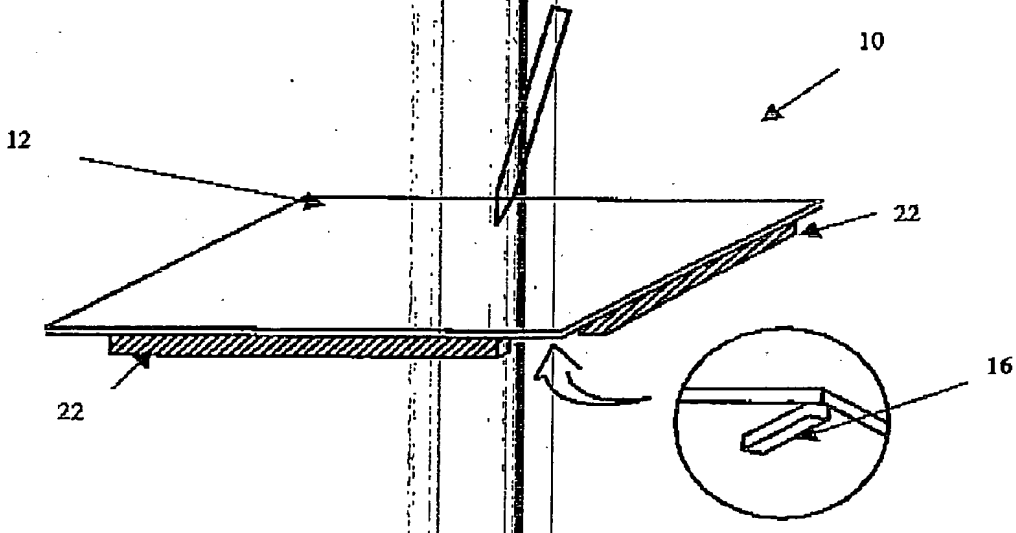

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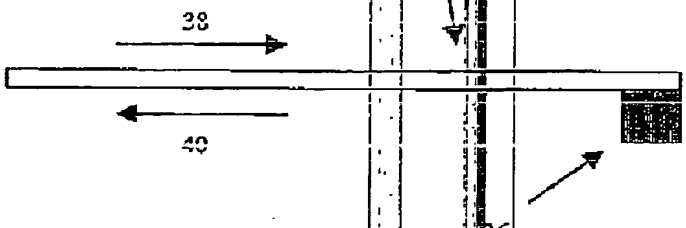
Fig 3



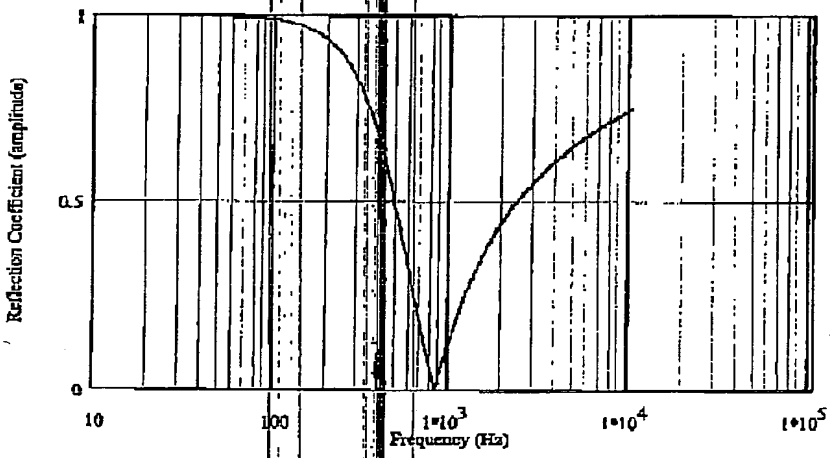


Fig. 4a:

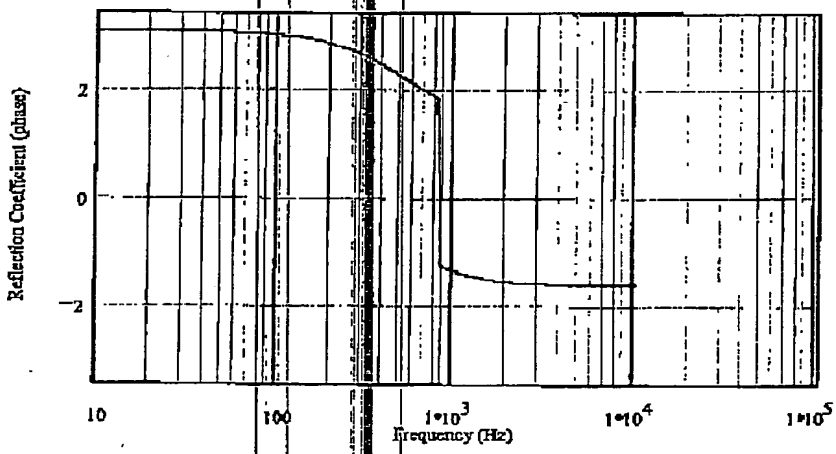


Fig 4b

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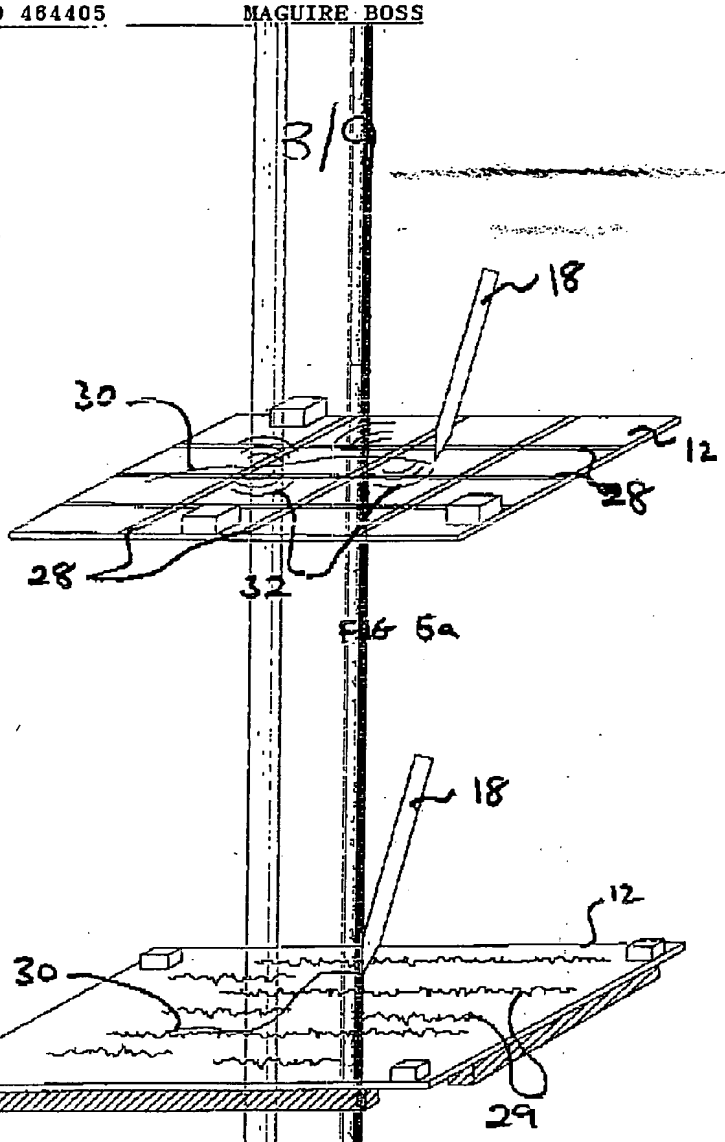

Fig 5a

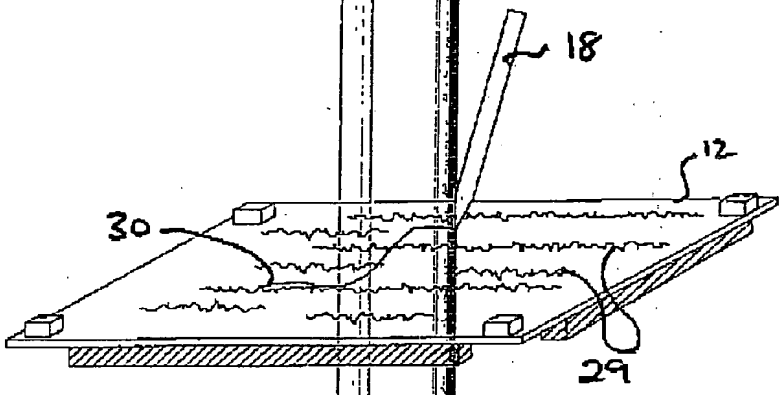

Fig 5b

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Fig 6

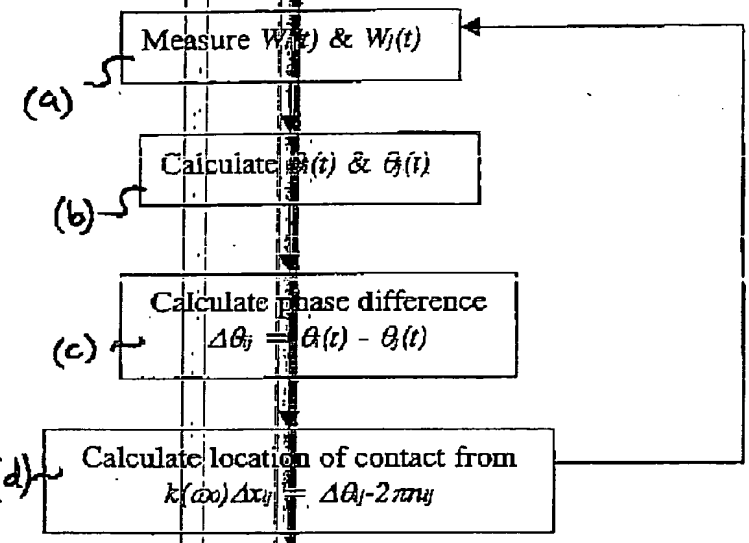
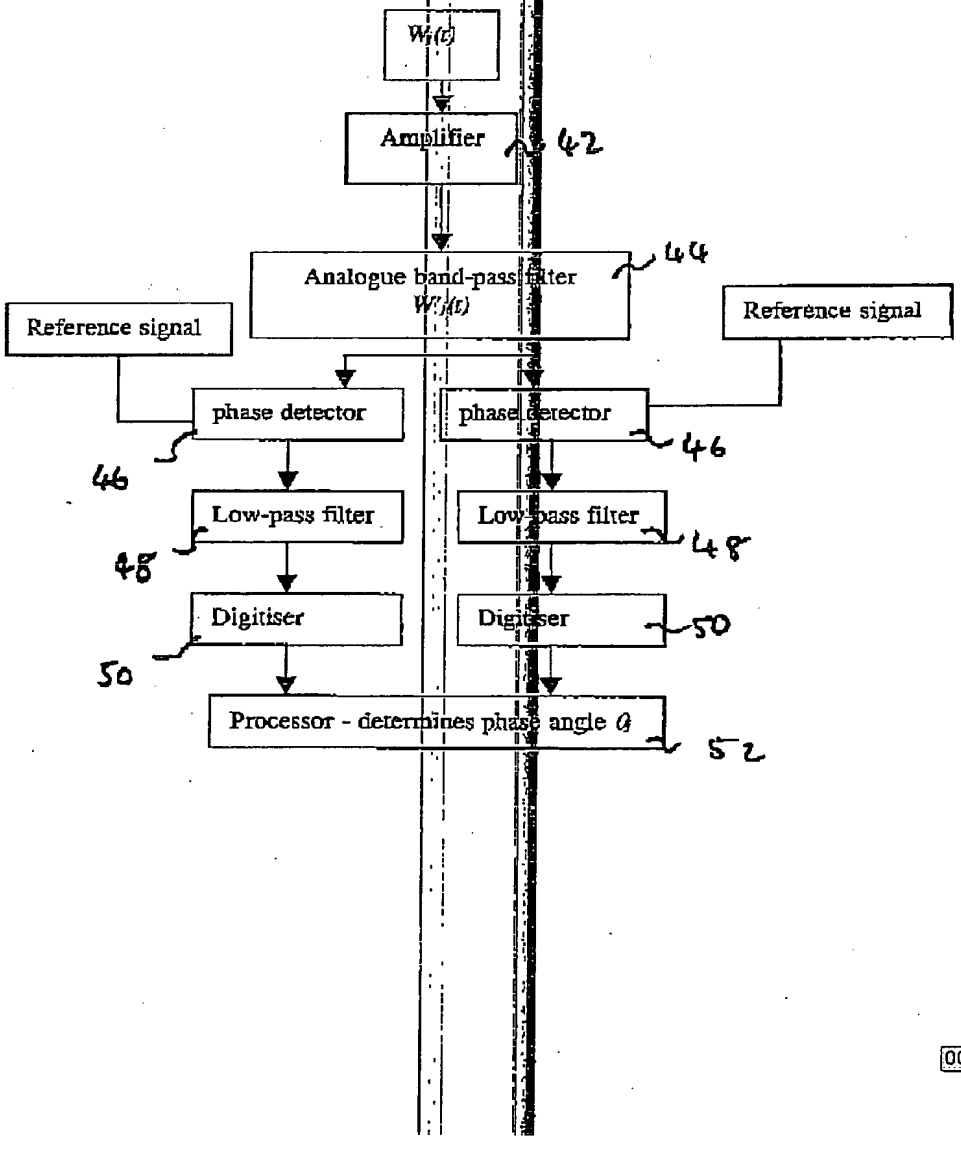


Fig 7a



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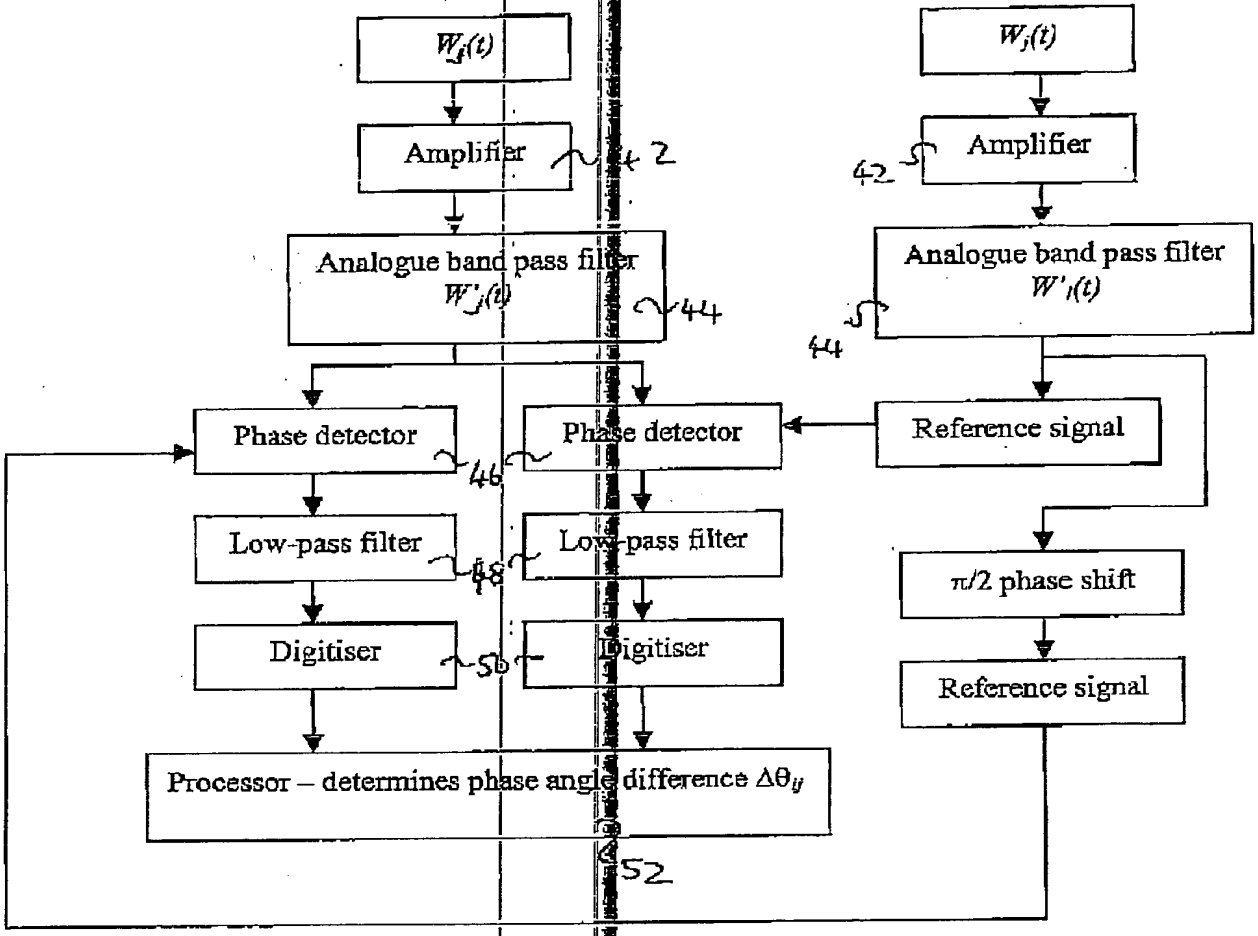
$W_i(t)$
Amplifier
42
Analogue band pass filter
$W'_i(t)$
44
Phase detector
46
Low-pass filter
48
Digitiser
50
Reference signal
$\pi/2$ phase shift
Processor – determines phase angle difference $\Delta\theta_{ij}$
52

FIG 4b

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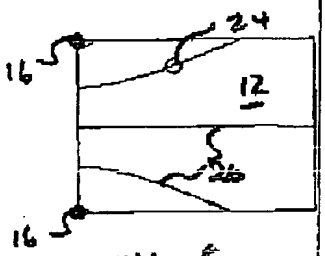

FIG 8a

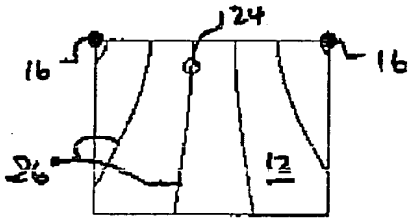

FIG 8b

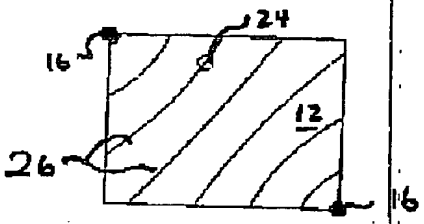

FIG 8c

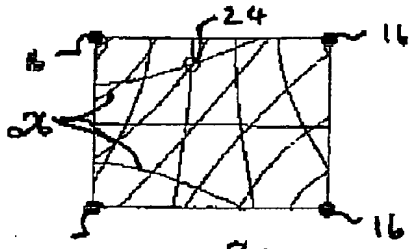

FIG 8d.

Fig 9

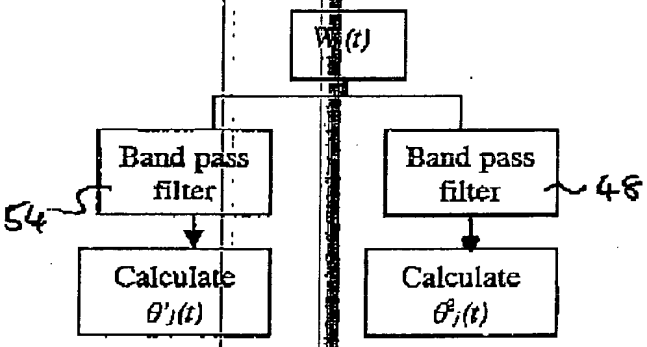

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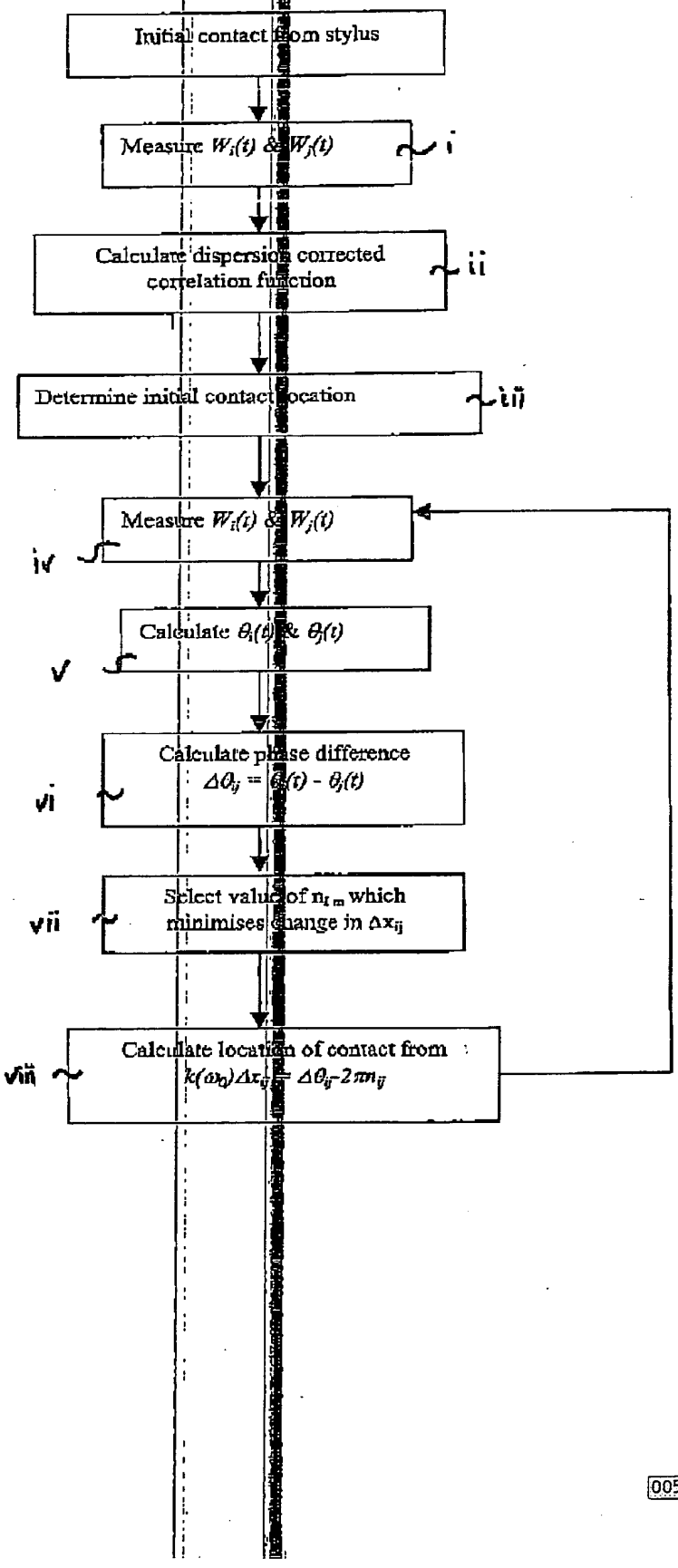
Fig 10



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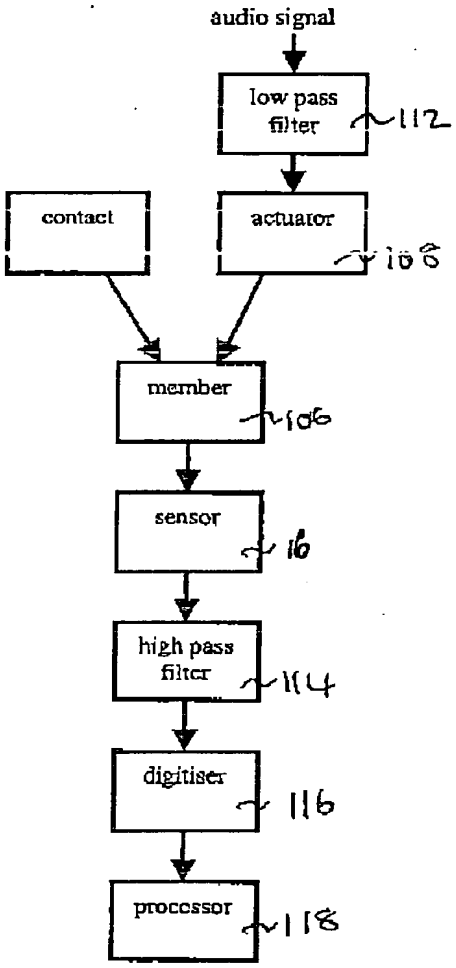

FIG 12a

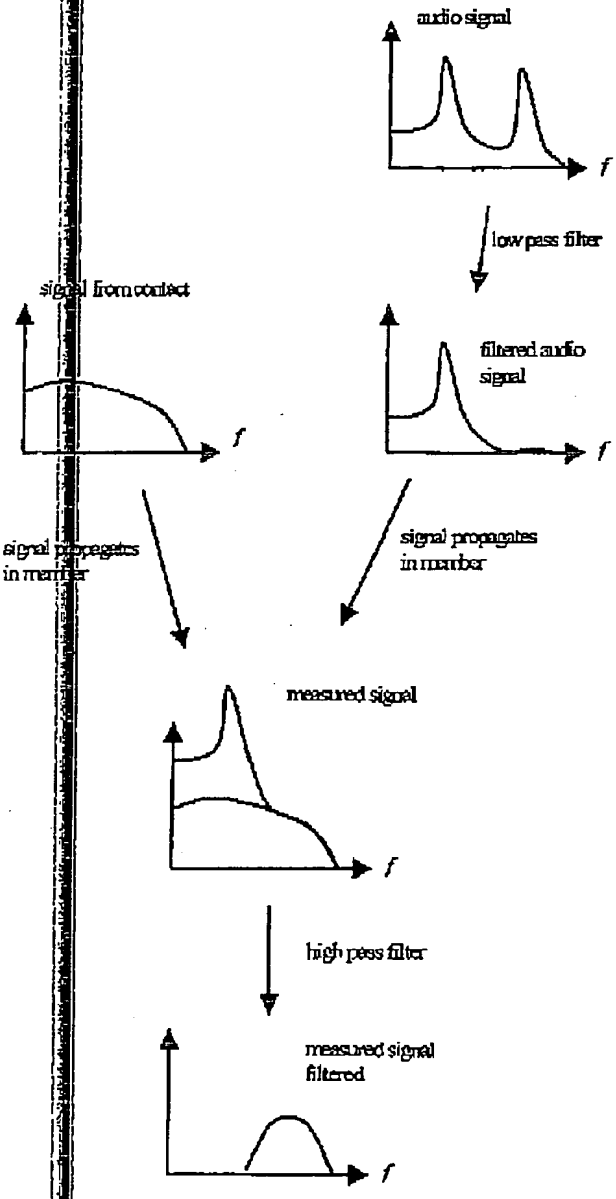

FIG 12b

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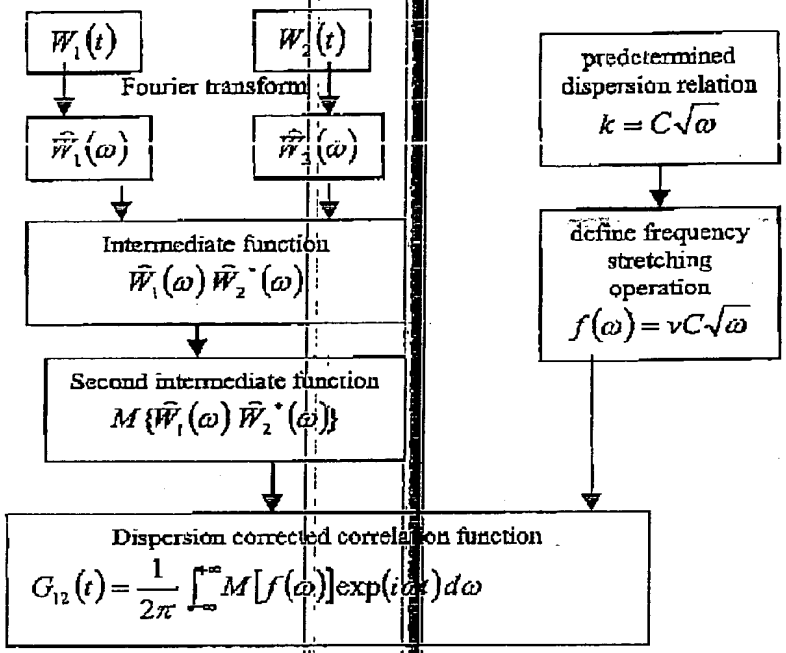
Fig 11



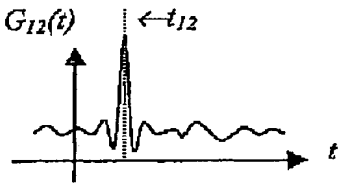


Fig 11a

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